Effect of the Ignition Method on the Extinction Limit for a Flame Spreading over Electric Wire Insulation

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Effect of the Ignition Method on the Extinction Limit for a Flame Spreading over Electric Wire Insulation

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Flame spread experiments with wire insulation were conducted in microgravity (parabolic flights) and in normal gravity to understand the effect of the ignition condition on the Limiting Oxygen Concentration (LOC) for an opposed air flow condition of 100 mm/s (typical flow velocity on ISS). Both the ignition power (50-110 W) and the igniter heating time (5-15 s) were varied. Polyethylene-coated Nickel-Chrome or copper wires with inner core diameter of 0.50 mm and insulation thickness of 0.30 mm were used as sample wires, and a 0.50 mm diameter coiled Kanthal wire was used as the igniter. The experimental results show that the LOC of NiCr core wires assume an almost constant value under normal gravity conditions once ignition occurred, whereas under microgravity conditions, the LOC gradually decreases as the ignition power or heating time increases and eventually it reaches an almost constant value. Thus, the effect of ignition condition on LOC is more evident in microgravity than in normal gravity. The variation in LOC value is about 2% within the tested range of ignition conditions. Finally, the results suggest that there exists a minimum ignition power and heating time to obtain the correct LOC values for electric wire combustion, especially in microgravity. In Cu core wire cases, the LOC monotonically decreases as the heating time increases because of preheating by the igniter. This preheating helps to sustain spreading during microgravity period. Future study is required to find the proper ignition condition for a high-conductivity wire. The results have the potential to improve safety aspects associated with the development of a fire safety standard for spacecraft.

I. Introduction

A fire accident is one of the most severe dangers in a spacecraft due to its completely enclosed environment and because it is difficult or impossible for the crew to evacuate[1]. To ensure the safety for astronauts, fire safety is an essential requirement for manned space mission. In a spacecraft, many electrical devices and cables are installed, and ignition of electrical wire is the most likely cause of fire accidents as a result of overloading or short circuiting. Materials intended to be used in spacecraft are generally screened by NASA's fire safety standard STD-6001B[2] to reduce the fire risk. In this standard, test 4 is applied for electrical wires. This test is used for evaluating electrical wire flammability under a given environment condition. However, this standard has some shortcomings when it comes to the evaluation of the flammability of electrical wires under microgravity environment[3]. One of the concerns with the method is that this test is conducted on the ground and it does not consider the effect of gravity on the flame behavior caused by the lack of natural convection. Since natural convection is almost absent, heat transfer

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from the sample to the ambient environment is reduced. So, the flammability of the materials become larger in microgravity According to Takahashi et al.[4], the most flammable condition of electrical wire does not exist in normal gravity, but rather in microgravity. Based on this fact, it is necessary to consider the effect of gravity elimination to evaluate the flammability of electrical wire under microgravity. The Limiting Oxygen Concentration (LOC) is often used as an index for a fire safety standard on the ground and could be an index applicable for material flammability evaluation in spacecraft[3]. The LOC is defined as the minimum oxygen concentration to sustain flame spreading under a given external flow velocity condition. In order to obtain the LOC values in experiments, the sample wire first has to be ignited by external heating such as a coil heater. However, if the heating by the igniter is not sufficient, the flame may extinguish even when the oxygen concentration is higher than the correct LOC value, and that causes large error in the determination of the LOC[6]. In this study, flame spread tests were conducted in normal- and reduced-gravity to investigate the effect of initial ignition condition on the extinction limit of spreading flame over wire insulation in terms of oxygen concentration. Then, the proper ignition condition to give a correct extinction limit was discussed. The proper ignition is defined as the ignition with an ignition power and heating time to attain steady-state flame spread when the oxygen concentration is higher than the correct LOC value.

II. Experimental apparatus and procedure

In this study, flame spread tests were conducted at both in normal gravity and reduced gravity provided by parabolic flights. Figure 1 shows the view of the inner combustion chamber of the experimental setup. A more detailed description is given in Citerne et al.[5]. The sample wire was mounted in the sample holder like Fig. 2, and the sample holder was placed at the center line of the chamber, and the coil igniter was placed at the top edge of wire insulation. The sample was ignited by applying electric current into the igniter, and the igniter was rigid for the entire ignition. After ignition occurred, the subsequent flame propagated downward against oxidizer flow, so opposed flow propagation was observed in this experiments. As a result of flame spread, the LOC of the sample wire was obtained under a given external flow velocity condition. The oxidizer flow came from the bottom of the chamber uniformly, then went out of the top of the chamber. The oxidizer flow was produced by mixing air with nitrogen. Figure 3 shows the igniter coil used in this experiments. The igniter was made of Kanthal wire with its wire diameter of 0.5 mm and 6 turns of wire were in this coil. Both the ignition power and the igniter heating time were varied ranging from 50 W to 110W and from 5 to 15 s as the parameters of the series of experiments.

The pressure inside the chamber was set to 1 atm and flow velocity was 100 mm/s during the experiments. Table 1 shows the specification of the sample wires. Every sample wire had a 13-cm long coating of polyethylene.

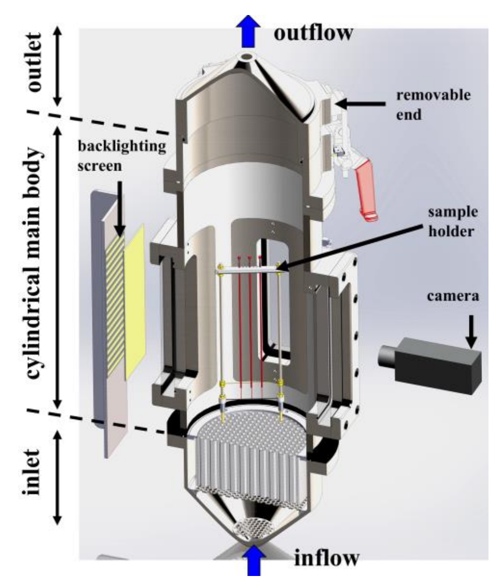

Figure 1. Schematic of experimental setup [5].

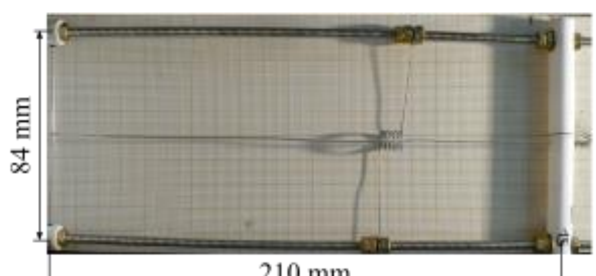

Figure 2. Configuration of sample.

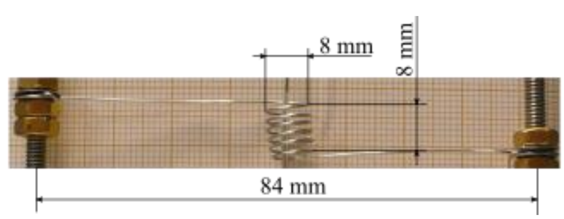

Figure 3. Picture of igniter.

Table 1. Sample wire specification

Inner core material	NiCr or Cu
Insulation material	Low density polyethylene
Core diameter [mm]	0.5
Coating thickness [mm]	0.3

III. Effect of ignition conditions on LOC

A. Results

When sustained flame propagation was achieved during the microgravity (μg) period of each parabola, it was defined as “Flammable”, and otherwise it was labeled “Extinction”, respectively. Thus, the LOC value for the μg experiments exists between the minimum oxygen concentration of “Flammable” cases and the maximum oxygen concentration of “Extinction” cases. In normal gravity (1g), the LOC was defined as the minimum oxygen concentration when the flame is sustained to propagate longer than 100 mm along the wire, whereas the distance covered by the flame in microgravity is about 20 - 40 mm depending on oxygen concentration and core materials. The parabolic flights were performed both in France and Japan with different experimental setups that have similar design concept, and all of the results taken in France and Japan are plotted in the same figure, as shown in Figs.4 and 5. The data obtained in France is noted as (A) and the ones from Japan as (B). The data points plotted in Figs. 4(a) and 5(a) represent the average of at least 3 test runs, and the data points plotted in Figs. 4(b) and 5(b) represent a single measurement.

Figure 4 shows the LOC values as a function of ignition power under a constant heating time, and Fig. 5 shows the LOC values as a function of heating time under a constant ignition power both in 1g and μg. In the tests for Fig. 4, the heating time was fixed at 8 s, and in the tests for Fig. 5, the ignition power was fixed at 70 W. The core wires of samples were Nickel-Chrome. The experimental results show that the LOC seems to be constant under 1g

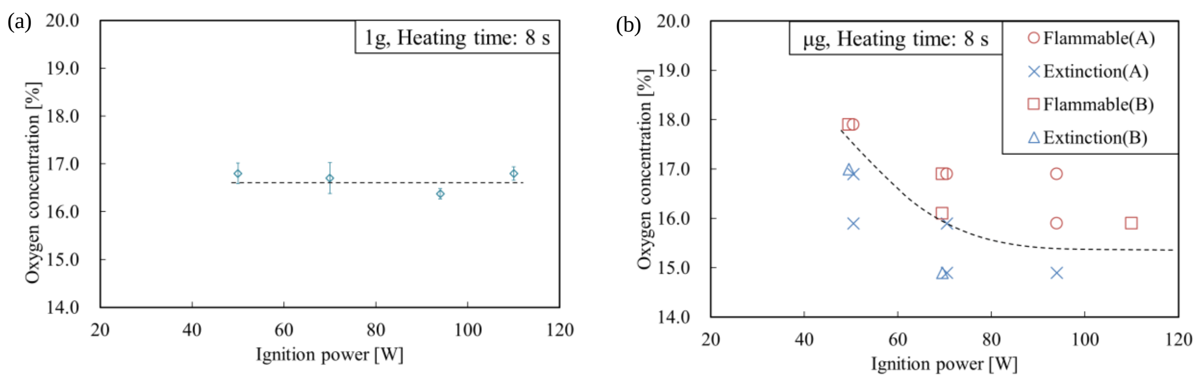

Figure 4. LOC of NiCr wire vs. Ignition power at 1g (a) and μg (b).

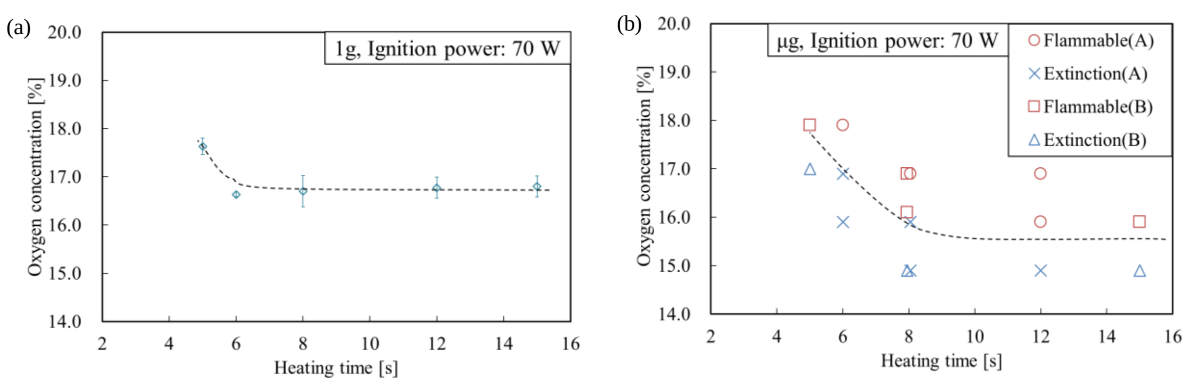

Figure 5. LOC of NiCr wire vs. Heating time at 1g (a) and μg (b).

conditions once ignition is carried out, whereas under μg conditions, the LOC gradually decreases as the ignition power or heating time increases, and eventually it reaches an almost constant value when the ignition power is 94 W or more, or heating time is 12 s or more. The variation range in oxygen concentration in the tested ignition power and heating time is about 2 %.

B. Discussion

In order to obtain the correct LOC value in experiments, the initial ignition condition to attain steady-state flame spread in oxygen concentration higher than LOC value should be given. According to Huang et al.[6], the additional heating after ignition occurs is required to achieve steady-state flame spread if the condition is close to the extinction limit. Therefore, when the ignition power or heating time is insufficient, the flame is not sustained even once ignition happens near the real LOC condition. On the other hand, the LOC reaches constant value once the sufficient additional heating is given. Meanwhile flame could be sustained after ignition even without sufficient additional heating as long as oxygen concentration is high enough. The conceptual understanding behind the trend in microgravity may result in the decrease of LOC with increase in ignition power or heating time and in reaching a constant LOC at high range of ignition power or heating time.

Compared with the normal gravity cases, the LOC in microgravity needs more heating to reach the constant value in the experiments. This is because the LOC of μG is lower than that of normal gravity, and at lower oxygen concentration, flame temperature becomes lower. Thus additional heating after ignition is required to achieve the steady flame spread.

IV. Effect of core wire

Figure 6 shows the LOC of Cu core wire at each heating time condition under microgravity environment. The LOC value monotonically decreases with increase in heating time and does not reach a constant value in the tested range. Cu has much larger thermal diffusivity than that of NiCr. So, the sample wire was preheated widely and this preheating has a strong effect on flame spread for short duration such as remained microgravity duration (20 s at most) after ignition.

In this case, it is difficult to find the proper ignition condition which provides the correct LOC value in experiments. To find the proper heating time condition for higher-conductivity wires, it is necessary to consider the temperature distribution corresponding to steady-state flame spread along the wire. Once the temperature distribution corresponding to the steady-state flame spread is accomplished by the igniter heating, the measured LOC value should be a proper one. Further, even if the preheating time is longer than that to give steady-state spreading temperature distribution the LOC value would approach the correct value finally after long term flame spreading. Therefore, it is essential to find such a critical heating time which can achieve the steady-state flame spreading temperature distribution and further research to find such a value is now going on.

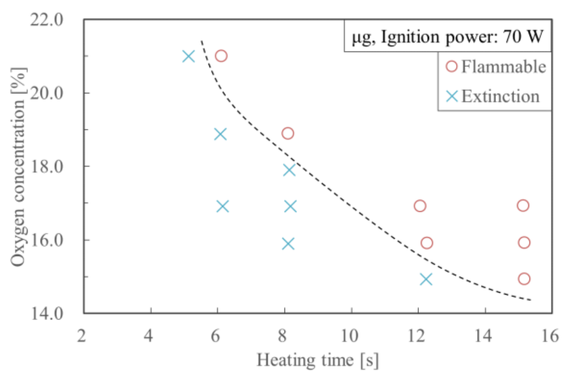

Figure 6. LOC of Cu wire vs. Heating time

V. Conclusions

This study investigated the effect of the ignition condition on the extinction limit for flame spread over a wire, both in normal gravity and in microgravity. The main conclusions of this study are:

(1) For the NiCr core wire, as the igniting power or the heating time increases, the Limiting Oxygen Concentration (LOC) gradually decreased and finally reached an almost constant value. There exists a minimum igniting power and heating time to obtain the correct LOC, especially in microgravity. This could be because additional heating is required after ignition in order to ensure not only ignition, but also steady flame spread.

(2) The effect of the ignition condition on the LOC value was more evident in microgravity than in normal gravity. This is due to the fact that the LOC in microgravity is lower than that in normal gravity, so more additional heating is required to achieve steady-state flame spread near the extinction limit.

(3) For the Cu core wire, as the heating time increased, the LOC decreased monotonically within the tested range of heating time, because the higher thermal conductivity of Cu results in increasing preheating distance with preheating time. This increased preheating distance helps to sustain the flame spread in microgravity.

These results have the potential to improve safety aspects associated with the development of a fire safety standard for spacecraft, and consequentially also to improve spacecraft fire safety in general.

Acknowledgments

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References

[1]Friedman, R., "Fire Safety in Spacecraft," *Fire and Materials*, Vol. 20, 1996, pp. 235-243.

[2]Ryschkewitsch, M., "Flammability, Offgassing, and Compatibility Requirements and Test Procedures" NASA-STD-6001B, 2011.

[3]Fujita, O., "Solid combustion research in microgravity as a basis of fire safety in space," *Proc. Combust. Inst.*, Vol. 35, 2015, pp. 2487-2502

[4]Takahashi, S., Ito, H., Nakamura, Y., and Fujita, O., "Extinction limits of spreading flames over wires in microgravity," *Combust. Flame*, Vol. 160, No. 9, 2013, pp. 1900–1902.

[5]Citerne, J.-M., Dutilleul, H., Kizawa, K., Nagachi, M., Fujita, O., Kikuchi, M., Jomaas, G., Rouvreau, S., Torero, J. L., and Legros, G., "Fire safety in space – Investigating flame spread interaction over wires," *Acta Astronaut.*, Vol. 126, 2016, pp. 500-509

[6]Huang, X., Nakamura, Y., and Williams, F. A., "Ignition-to-spread transition of externally heated electrical wire," *Proc. Combust. Inst.*, Vol. 34, No. 2, 2013, pp. 2505–2512.